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Innovative Approaches to using the International Space Station as a Mars Transit Analog

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Abstract

Human research on the International Space Station (ISS) crew has made significant advances in understanding of the effects of physiology on human health in space missions. However, ISS has not been as suitable for research on other hazards of human spaceflight such as isolation and communications delay. NASA recently completed a special assessment of whether modifications could be made to operations or facilities so that ISS could be used more effectively as an analog to simulate long-duration crew missions beyond low earth orbit. A cross-disciplinary team¹ met to identify concept of operations, trade spaces, challenges, and opportunities to making

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ISS more operationally relevant as a Mars transit mission analog, and the results and implementation plans are summarized in this manuscript. In addition to the use case of 12-month missions (already in planning by the NASA ISS Program to bound expected Mars transit durations), three new use cases where ISS could provide valuable high-fidelity experience were identified. (1) Testing of operations procedures and medical care could be enhanced by demonstrating crew handling a simulated medical event in microgravity, autonomously, and with significant communications delay. (2) Isolation and confinement effects of deep space transit could be studied on ISS to validate current habitable volume requirements for Mars transit as well as provide context for evaluating the results of the extensive ground-based simulations in HERA and NEK. A trade study of possible operational and hardware changes that would make ISS applicable to these use cases was completed. (3) Surface operations after the physiological deconditioning of a long transit could be conducted to validate crew ability to perform critical ground tasks after 6-month Mars transit and aid in conceptual design of Mars surface element architectures.

Each of the case studies includes a trade space between operational impacts on nominal ISS activities and degree of fidelity. A phased approach to implementation means that several “quick start” activities can be done in 2019-2020 at the same time as planning continues for more complex exploration analog options beginning as early as 2022. The team determined that many of these quick-start tasks could be done with available assets, entirely independent of other exploration system development timelines (such as Orion, Space Launch System). The consideration of the full suite of human spaceflight capabilities in the lunar vicinity can also be included as each step in human exploration serves as a simulation opportunity for some aspect of subsequent missions. Further discussions of options with the international community are critical for considering the benefits as well as impacts of simulation activities on ISS, as well as to better formulate future mission architectures.

Keywords: NASA, ISS, human spaceflight, space exploration missions, analogs, simulations, isolation, Mars transit, medical operations, autonomy, communications delay

1. Introduction

From the beginning of human spaceflight, scientists and engineers have sought appropriate analogs to extreme missions where human performance can be tested in order to improve engineering design, medical requirements and countermeasures, and ultimately ensure missions safety and success. For example, the Extended Duration Orbiter Medical Program [1] and NASA-Mir Missions [2] were both designed to gain the medical information necessary to reduce the risks of human spaceflight both on the International Space Station (ISS) and subsequent exploration missions beyond Earth orbit. From its inception, ISS has served

as a key place for doing research on the effects of microgravity on human physiology and developing mitigations and countermeasures to those effects to enable future exploration [3, 4].

The effects of low gravity and gravity transitions are only one of the spaceflight hazards to human health and performance. Spaceflight risks to the human system are categorized as resulting from one of five hazards of human spaceflight [5, 6].

(1) *Altered gravity fields* create risks such as disorientation and sensorimotor disruption [7], fluid shifts and visual alterations [8], and without suitable exercise would generate cardiovascular deconditioning [9] and bone

loss [10]. These areas have been the foci of significant scientific progress made during the ISS research era [11].

(2) *Radiation exposure* can cause acute in-flight effects, central nervous system and cardiovascular changes, as well as affect long-term cancer risks of crewmembers after they return [12]. To date, most studies have been conducted at simulation facilities such as the National Space Radiation Laboratory [13] because radiation exposure on ISS within the magnetosphere is not equivalent to deep space radiation.

(3) The *distance from Earth* is a hazard that increases the further crewmembers explore, with risks associated from lack of consultation with the ground due to communication delays and the need for autonomy of the crew in solving problems from repairs to medical events [14]. Communications with ISS have a one-way communications delay of <0.25 s, and communications interruptions of minutes during certain positions of the Tracking and Data Relay Satellite (TDRS) system [15]. In contrast, Mars missions will have communications delays of 4-24 min depending on the position in the trajectory, and blackouts/whiteouts of up to 2 weeks during solar conjunctions [16, 17]. Thus exploration crews will need onboard information to operate without ground support in a mode far different than current operations on the ISS. A medical evacuation from the ISS could be completed within 3.5 h, but emergency evacuations during Mars missions have extremely limited windows of opportunity due to celestial mechanics.

(4) *Isolation and confinement* is a significant risk to the crew as many months are spent with a small number of companions in a small space, away from Earth and family. Some of the associated risks include behavioral effects of isolation on crew performance and sleep disorders [18].

(5) A final hazard is the effects of the crew being in a *hostile closed environment*, with

vehicle design having a significant impact on their well-being. Confined in spacecraft with recycling of the atmosphere, these risks are associated with environmental exposures such as CO₂ levels, toxic exposures from materials or leaking fluids, and possible changes in the microbes present in the environment and in the environmental control and life support systems [19]. The need to bring or cultivate food brings a set of nutrition risks to long missions in closed environments [20].

Typically Earth-based analogs have been used to model isolation, confinement and remote conditions of exploration mission scenarios—volunteers have participated in simulations and investigations in the Human Exploration Research Analog (HERA) in the U.S. [21] and Russian *Nazemnyy eksperimental'nyy kompleks* (NEK or “Ground-Based Experimental Complex”) facility in Russia [22]. These facilities offer conditions and levels of control of missions that are not available in our current human spaceflight missions on the ISS.

2. Changing ISS Operations to be a Better Analog for Deep Space Exploration

In July 2017, the NASA ISS Program (ISSP) and Human Research Program (HRP) agreed to identify studies with exploration relevance that could not be completed on ISS as it currently exists, but that would be possible if operations were altered so that ISS was a better analog for exploration. By thinking of ISS as an analog for Mars transit, not only for physiological effects of gravity, but also for performance across all spaceflight hazards, additional studies could be conducted. Being able to study all five hazards of human spaceflight and integrated hazards simultaneously would allow ISS to make significant additional contributions to Mars exploration readiness (Table 1).

Table 1. ISS Modifications and Constraints for Modeling Mars Transit Hazards to the Human System

Altered Gravity Fields
<ul style="list-style-type: none"> Physiological shifts due to microgravity environment.
• Radiation
<ul style="list-style-type: none"> ISS radiation exposure is made up of 50% protons and 50% galactic cosmic rays (GCR), while deep space transit would be dominated by GCR (assuming shielding for solar particle events)
• Distance from Earth
<ul style="list-style-type: none"> Simulated communication and data delays Autonomous hardware Support tools for crew autonomous operations Exploration-like Training Paradigms
• Isolation and Confinement
<ul style="list-style-type: none"> Limited communication with families and ground support Limited habitable volume (25m³/person is the exploration standard² [23], ISS is spacious at about 65m³/person) No vehicle traffic No care packages or fresh supplies No window views of Earth Exploration-like sleeping quarters
• Hostile Closed Environment
<ul style="list-style-type: none"> Atmosphere/Environment (current ISS carbon dioxide level is higher than expected for exploration) Exploration food system (may include less variety, but also bulk ingredients and crop production) Compact exploration exercise devices (preferred) Exploration-type hygiene, medical, and other technologies (less disposability, preferred)

Use of ISS as a deep space analog would require changes in the status quo of ISS operations. Possible benefits of such utilization could include studies of increased duration and the role of mission duration in human response to microgravity, isolation and confinement effects of deep space transit, testing of operations procedures and medical care, and surface operations after the physiological deconditioning of a long transit. However, the changes that would need to be made to facilitate such applied research

could have periodic impacts on other utilization of ISS.

A “Tiger Team” of interdisciplinary NASA experts [1] was assembled to develop potential use cases and associated challenges and benefits for further evaluation by the programs. The work of this team, its reporting milestones, and follow-on discussions are summarized in Table 2.

Table 2. Milestones in concept development for new uses of ISS as an exploration analog.

October 2017	Tiger Team initiated.
July 2018	Report to programs on three possible new use cases, and follow-on actions for concept development.
September 2018	Trade study determines that closing off hatches of ISS to achieve exploration-like volumes is not feasible without significant impacts to utilization.
October 2018	ISS4Mars Workshop hosted by the Agenzia Spaziale Italiana (ASI), discussion of use cases and strategy with ISS International Partners.
February 2019	ISS and HRP joint planning assumptions for implementation of use cases.
May 2019	Additional working team initiated to define landing simulation concept of operations for Commercial Crew Program (CCP) returns from ISS.
July 2019	ISS begins planning for additional 1-year missions to begin with the launch of crew via commercial US providers.
September 2019	NASA-Russia joint technical interchange meeting on implementing the use cases.
October 2019	IAC Special Session International Discussion
November 2019	ISS, CCP and HRP decisions on “Field Test 2” landing simulation concept.

2.1 One-year missions as Mars transit analogs

The duration of a one-way microgravity transit to Mars depends on the choice of

² 25 m³/person is based on a crew of 6 for a 30 month mission with additional assumptions [23]

propulsion technology and assumptions about advancement in those technologies in the future, as well as mass assumptions. Mars Design Reference Architecture 5 [24] postulated conjunction-class mission transit times of about 180 days eachway, a Mars stay time of around 500 days, and a total mission duration of about 30 months. The total in-space time of about 1-year has been used in planning the HRP Path to Risk Reduction for a decade (Human Research Program 2019). As alternative technologies and architectures continue to be considered, new technologies could shorten transit times, but alternate architectures could also lengthen the transit times. Regardless of changes in architecture, investigating the risks of missions significantly longer than current 6-month ISS missions is critical [25].

NASA and Roscosmos jointly completed the first 1-year missions (340 days) of cosmonaut Mikhail Kornienko and astronaut Mark Kelly to the International Space Station in 2015-2016. These represented the first yearlong missions since Sergei Avdeev's mission to Mir in 1999 (Figure 1). Two other NASA astronauts have completed missions that were longer than typical 6-month ISS missions (Peggy Whitson for 289 days in 2016-2017, and Christina Koch is currently on ISS and expected to stay for around 325 days). However, since each crewmember participated in different experiments during their missions it is hard to generalize across the small datasets. Generally, scientific data show differences between 6- and 12-month missions, including changes in gene expression and biomarkers [26]. Anecdotal reports indicate symptoms such as lower body pain, skin sensitivity, rashes, and fogginess following extended missions that were not observed in previous 6-month missions [27].

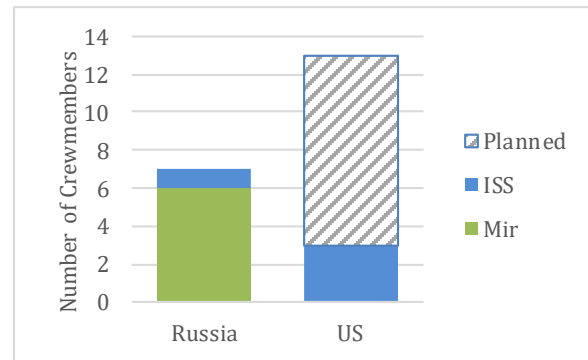


Figure 1. Mars Transit Class (> 9 month) Mission Experience

Key to advancing understanding of the risks of a Mars transit to human health is to systematically collect data on crewmembers that stay for different durations, so that duration can become the independent variable in a comprehensive study. HRP has selected over 25 proposals for such a study focused on the physiological and psychological adaptations of long-duration spaceflight and is currently integrating them into a single experiment package. The studies will be anchored by a battery of “standard measures”—biochemical, physiological, and human performance tests taken at consistent intervals before, during and after spaceflight. These measures have been designed to consolidate and systematically monitor astronaut health and performance and “provide the widest dissemination of data to assist other investigators in quantifying the human health and performance risks associated with human spaceflight or exploration missions” [28] [29].

The ISS Program plans to implement a staggered set of missions with durations of approximately 1-year, 6-months and 6-weeks as soon as the Commercial Crew Program begins transporting astronauts to the ISS, as early as 2020 (Figure 2).

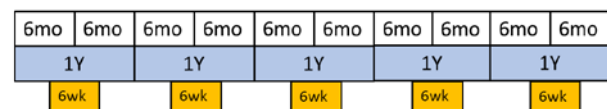


Figure 2. Notional timeline for staggering crewmembers for different durations of ISS missions.

2.2 Medical autonomy

Over a period of 1-2 days on ISS, it would be possible to demonstrate the exploration paradigm for operations in flight medicine and crew autonomy in providing medical care to each other. Nominal activities could include private medical conferences conducted via store-and-forward communications (rather than over space-to-ground links), self-exams, and health maintenance activities. A credible catastrophic medical event could be simulated while also evaluating software tools and crew performance. After consultation between the ISSP and HRP, a “quick-start” contingency operations activity without ground support is planned for spring 2020. This activity will use autonomous software upgrades to the ultrasound system.

The ISS Program also made software modifications to enable simulated communications delays including space-to-ground, video, and store-and-forward (text-like) communications. This capability will be available in the fall 2019.

Once these activities are complete, HRP and ISS will plan additional 1-2 day medical simulations on orbit with the possibility of completing up to four different simulations over the next several years. Contingency simulations will be implemented iteratively and include medical events such as sepsis, autonomous diagnosis and treatment with exploration-like capabilities, just-in-time training and guided procedures, and delayed consultation with ground.

2.3 Systems Autonomy, Crew Autonomous Operations and Communications Delay

Medical autonomy simulations as well as hardware autonomy testing done in the past (e.g., [30]) are pathfinders for possible future extensions of autonomous operations to longer duration simulation studies. A number of hardware and software developments are needed to mirror the types of systems that

would be used for deep space exploration. Decision tools and monitoring capabilities enable exploration-like autonomy of the crew [31]. Once tools and systems are developed they must be tested in appropriate environments and a variety of operational scenarios. The new communications delay capabilities and possibility of an “exploration operations” mode on the ISS is a significant enabler of making future exploration safer and more successful.

However, other users of ISS may find an exploration mode of operations to be less desirable. For example, ISS National Lab users and international partners will probably not want to invest in making research systems more autonomous. Many scientists benefit from ready communications with the crew doing their work, so not all experiments will be able to successfully operate during periods of simulated crew autonomy.

FOD and ISS will work together in 2020 to identify a path to extending autonomy studies (with or without communications delay) for longer blocks of time up to 2 weeks. The effort will include approaches for crew/ground interactions, simulating autonomous operation of an exploration vehicle while ISS is still under significant ground control, and approaches for suspending the simulation in the event of an emergency.

Once the plan is approved, exploration technology and research users including HRP will be able to target specific studies to those periods of operations. From this incremental progression, flight operators and crew will gain valuable experience and lessons learned to shape the development of deep space operations approaches, and HRP can use these periods of time to study the effects of isolation and confinement and simulated distance from Earth on the behavioral health and performance of the crew. As autonomous periods are extended, the ISS program will have to juggle schedules to cluster exploration-like activities in the autonomous

periods. Some previous autonomy studies on ISS have identified efficiencies in crew preferences and possible efficiencies in crew time that come from self-scheduling as opposed to control of schedules from the ground [32]. It is possible that ISS will identify benefits and options for more efficient activities from these autonomy tests.

2.4 Sensorimotor performance for landings of long-duration crew

The final use case expands from the recently completed studies of crew sensorimotor impacts after landing on Soyuz spacecraft in Kazakhstan (Field Test [33] [34]). Crew performance after long-duration space exploration missions, especially in the hours immediately post-landing, is not well-understood and could drive Mars architecture decisions and operations planning. For example, if crew are not immediately able to don a heavy spacesuit, open a hatch, and egress from their landing craft, the lander will have to be large enough for the crew to live in until they re-acclimate to gravity. Knowing how long this recovery period is will enable spacecraft designers to properly size a Mars lander, or seek less risky options for the crew to transfer to a habitat [35]. Crew performance data immediately after landing will also help mission managers assess and plan for contingency operations.

The critical operational window for human performance and sensorimotor adaptation in the first few days after landing. If all goes well, the crew could recover and adapt to Martian gravity within the lander. However, there are contingency scenarios that will require crews deconditioned from long transits to perform critical tasks within the first 24 hours after landing. One area of focus is the connection to surface power before lander battery power is depleted. Although it is expected that the primary connection would be made by automated robotics, crew telerobotic control should be considered in contingency planning. Other

early contingency activities that might be necessary for the crew to perform are early egress from the lander to a rover and extravehicular activities. Currently, ISS long-duration crews land on Soyuz in Kazakhstan and do not return to Houston until around 24 hours post-landing. Science less than 24 hours after landing has been limited to sensorimotor assessment tasks performed as part of the Field Test investigation at the landing site and while returning to Houston.

ISS long-duration crews landing on Commercial Crew Program (CCP) vehicles will provide an opportunity to thoroughly study crew performance for functional Mars tasks from zero to 24 hours post-landing, or even longer. Water landings are likely to introduce significant additional sensorimotor challenges and are probably not good analogs for Mars landings. However, Boeing CST-100 flights plan desert landing sites in the U.S. and could be excellent analogs for crew performance after landing on Mars.

A key in defining new concepts of operations is to connect to the past results of Field Test, while adding operationally relevant tasks in a way that makes a meaningful contribution to future exploration architectures and operations. The significant physical challenges experienced by crew returning from extended ISS missions means that testing to define performance boundaries can be extremely uncomfortable [34]. A special team partly derived from the team in this paper is now looking at different operational concepts to make a recommendation to ISS, CCP, HRP and flight operations leadership for future plans. The new team is looking at concepts of operations and what mobile capabilities would be required. To inform the planning, a quick-start of crew telerobotic performance capabilities and fine motor skills during returns from Kazakhstan in the first 24 hours after the 57S Soyuz landing was tested in June 2019 as an extension of the Robotics On Board Trainer (ROBoT) Investigation on

crew training and performance for fine sensorimotor tasks. If approved, it is expected that such landing studies would begin on the 3rd CST-100 landing (no earlier than 2022).

Operationally relevant and scientifically structured post-landing research on sensorimotor performance has the potential to inform risk posture, future study after Lunar landings, and the development of the Mars landing architecture.

3. Use cases that ISS cannot meet at this time.

The ISS Program was able to take on a number of potential modifications of operations and hardware to serve as an exploration analog. However, there were some concepts that had numerous challenges, making it difficult to find a feasible implementation approach. Some may become possible as experience is gained with other use cases.

3.1 Isolation and confinement in exploration volumes

ISS is significantly more spacious per person than the minimum working standards used for architecture planning (Table 1). As such studies are considered, options for adding elements of isolation and confinement (such as smaller volumes) could also be revisited.

We conducted a trade study of options for confining crew in smaller volumes. There were several significant constraints. (1) If hatches were to be closed, crew needed to have unimpeded access to their rescue vehicle, meaning that such a division could not be considered until Commercial Crew Program vehicles are serving the ISS. (2) Separation of the U.S. Operating Segment (USOS) and Russian Segment (RS) volumes would be a significant disruption to daily operations because the crew moves freely throughout ISS each day to access equipment

for exercise and research. (3) It is impossible to divide the crew into two separate volumes without the full agreement of all international partners, because it will affect the activities and living patterns of all crewmembers. (4) Within the USOS, some additional modules would have to be blocked in order to get small enough volumes, making it necessary to reconfigure modules, toilets, sleep stations and other necessities, and also limiting access to research facilities (Figure 3). (5) A final set of impacts were on the life support systems due to the reconfiguration and blocking of airflow through modules. After looking at many different operational configurations, we determined that there was no near-term way to meet scientific needs without significant impacts to other science utilization and the facility configuration.

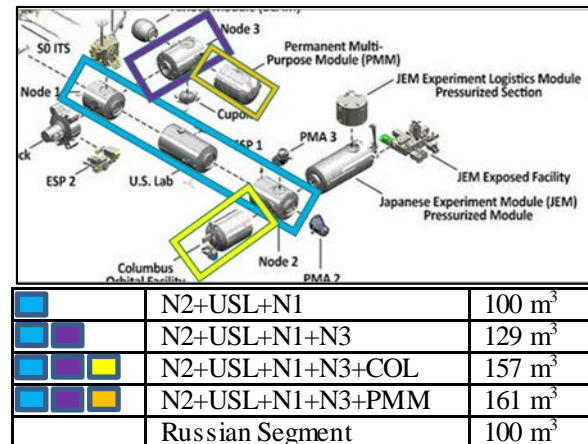


Figure 3. Alternate volume configurations considered in the trade study targeting about 100m³ for 3-4 people [23]. All configurations considered had such significant impacts that they were not feasible.

In the future other modules may be attached to ISS or be available as stand-alone vehicles as part of the commercial development of low-Earth orbit [36] [37]. Planning concepts for a Gateway in cis-lunar orbit could also be used as analogs for Mars transit habitat volumes [38]. Both of these could provide opportunities for future isolation and confinement studies in volumes

more similar to those expected for deep space transit.

3.2 *Autonomy or communications delay studies for longer than 1-2 weeks*

Ideally, HRP would like to carry out a 30-45 day study to compare and validate with 30-45 day studies conducted in the HERA analog with similar standard measures of physiology and performance. Due to the uncertainties and potential impacts, after the 1-2 week studies are complete, both programs can reevaluate the challenges and value of longer duration autonomy studies.

3.2 *Hardware, software and crew autonomy that is relevant for exploration missions*

One aspect that needs clarity is whether lack of communication with the ground in normal daily operations affects efficiency. There are also distinct differences in the current and future capabilities for autonomous testing. Autonomous hardware that is designed to operate without crew input, but may need ground monitoring may not be representative of exploration operations. Software systems and tools that are designed

to help the crew to solve problems without consulting the ground might be very useful to test. ISS crewmembers have reported strong interest in reducing reporting and scheduling interfaces with the ground in daily activities, and job aids to support routine operations might be quite different than aids for contingency or repair activities.

4. **Summary and Conclusions: Overall exploration analog strategy**

By making temporary changes in the approaches to ISS operations, aspects of deep space exploration can be modeled, and the platform can be used to advance Mars readiness. Although final details have yet to be completed, the ISS Program is able to pursue significant opportunities to improve its relevance as a Mars exploration analog. Just as it took years of operational experience before NASA was ready to initiate 1-year crew missions, so too will extensions of the duration of other simulations develop once shorter operational tests are successful. Knowledge to be gained on crew medical operations, autonomous operations and communications delay, long-duration effects of microgravity, and crew performance

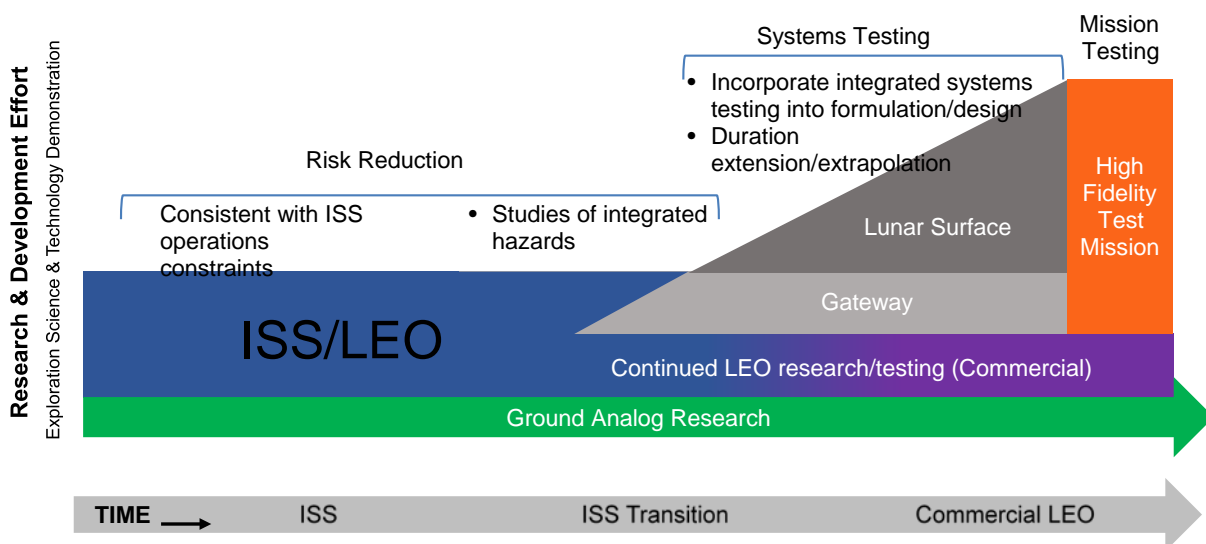


Figure 4. Notional human spaceflight strategy for integrated research and testing for Mars mission readiness.

following transition to a planetary surface all are important for exploration mission architectures. Assumptions about crew health and performance can be significant drivers of basic assumptions such as mass to orbit and mass of landers that are significant drivers of feasibility, cost and schedule.

One result of international discussions of ISS as an exploration analog is the recognition that every platform—whether ISS, commercial LEO, lunar Gateway, or lunar surface—has relevance to future Mars missions. However, by being clear about the hazards that are reproduced, simulated, or absent, we can be wise in using different platforms to increase operational capabilities and reduce risks in future missions.

Exploration-relevant testing is a key part of the demand for access to LEO as ISS transitions to commercial platforms [36]. Making changes to ISS operations to match exploration mission approaches can have impacts on other users of the U.S. National Laboratory, but it should be possible to balance access by both types of users. Exploration research is needed by NASA to validate systems, operations, and crew performance using LEO as a place to prepare for deep space exploration missions. Operational evolution and simulation of deep space operations and hazards is both an important objective for ISS today, as well as for commercial providers in LEO after ISS transition is complete (Figure 4).

References

- [1] C. F. Sawin, G. R. Taylor and W. L. Smith, Extended Duration Orbiter Medical Project, Vols. NASA/SP-1999-534, NASA, 1999.
- [2] I. B. Gontcharov, I. V. Kovachevich, S. L. Pool, O. L. Navinkov, M. R. Barratt, V. V. Bogomolov and N. House, "In-Flight Medical Incidents in the NASA-Mir Program," *Aviation, Space, and Environmental Medicine*, vol. 76, no. 7, pp. 692-696, 2005.
- [3] Institute of Medicine, Safe Passage: Astronaut Care for Exploration Mission, Washington, DC: National Academies Press, 2001.
- [4] Human Research Program, Human Research Roadmap: A Risk Reduction Strategy for Human Exploration, Houston, Texas: NASA, 2019.
- [5] M. Löbrich and P. A. Jagger, "Hazards of human spaceflight," *Science*, vol. 364, no. 6436, pp. 127-128, 2019.
- [6] L. J. Abadie, C. W. Lloyd and M. J. Shelhamer, "The human body in space," 2018.
- [7] M. Shelhamer, "Trends in sensorimotor research and countermeasures for exploration-class space flights," *Frontiers in Systems Neuroscience*, 2015.
- [8] M. B. Stenger and W. J. Tarver, "Evidence Report: Risk of Spaceflight Associated Neuro-ocular Syndrome (SANS)," NASA Human Research Program, Houston, Texas, 2017.
- [9] R. L. Hughson, J. K. Shoemaker, A. P. Blaber, P. Arbeille, D. K. Greaves, P. P. Pereira-Junior and D. Xu, "Cardiovascular regulation during long-duration spaceflights to the International Space Station," *Journal of Applied Physiology*, vol. 112, no. 5, pp. 719-727, 2012.
- [10] J. Sibonga, T. Matsumoto, J. Jones, J. Shapiro, T. Lang, L. Shackelford, S. M. Smith, M. Young, J. Keyak, K. Kohri, H. Oshima, E. Spector and A. LeBlanc, "Resistive exercise in astronauts on prolonged spaceflights provides partial protection against spaceflight-induced bone loss," *Bone*, 2019.

- [11] J. A. Robinson, K. A. Costello and D. Brady, *International Space Station Benefits for Humanity*, 3rd ed., Vols. NP-2018-06-013-JSC, Houston: NASA, 2018.
- [12] J. C. Chancellor, R. S. Blue, K. A. Cengel, S. M. Auñón-Chancellor, K. H. Rubins, H. G. Katzgraber and A. R. Kennedy, "Limitations in predicting the space radiation health risk for exploration astronauts," *npjMicrogravity*, vol. 4, 2018.
- [13] C. La Tessa, M. Sivertz, I. H. Chiang, D. Lowenstein and A. Rusek, "Overview of the NASA space radiation laboratory," *Life Science Space Research (Amst.)*, vol. 11, pp. 18-23, 2016.
- [14] J. R. Davis, R. Johnson, J. Stepanek and J. A. Fogarty, *Fundamentals of aerospace medicine*, 4th ed., Philadelphia, PA: Lippincott, Williams and Wilkins, 2008.
- [15] Tracking and Data Relay Satellite Project, "Tracking and Data Relay Satellite: Continuing the Critical Lifeline of Communications," NASA Goddard Spaceflight Center, Greenbelt, MD, 2012.
- [16] W. D. Nason and J. C. Hoagland, "Comments on the communication and data problems associated with a Mars trip during a conjunction phase," *IEEE Transactions and Aerospace and Electronic Systems*, Vols. AES-3, pp. 28-43, 1967.
- [17] D. Morabito and R. Hastrup, "Communicating with Mars during periods of solar conjunction," *IEEE Aerospace Conference*, p. 4.1306, 2002.
- [18] J. I. Pagel and A. Choukèr, "Effects of isolation and confinement on humans-implications for manned space explorations," *Journal of Applied Physiology*, vol. 120, pp. 1449-1457, 2016.
- [19] R. J. Bruce, C. M. Ott, V. M. Skuratov and D. L. Pierson, "Microbial Surveillance of Potable Water Sources of the International Space Station," *Journal of Aerospace*, vol. 114, pp. 283-292, 2005.
- [20] M. Cooper, G. Douglas and M. Perchonok, "Developing the NASA Food System for Long-Duration Missions," *Journal of Food Science*, vol. 76, no. 2, pp. R40-R48, 2011.
- [21] L. B. Landon, K. J. Slack and J. D. Barrett, "Teamwork and Collaboration in Long-Duration Space Missions: Going to Extremes," *American Psychologist*, vol. 73, no. 4, pp. 563-575, 2018.
- [22] B. J. Corbin and L. M. Vega, "NASA's use of Ground and Flight Analogs in Reducing Human Risks for Exploration," *Frontiers in Physiology. Conference Abstract: 39th ISGP Meeting & ESA Life Sciences Meeting*, 2018.
- [23] A. Whitmire, L. Leveton, H. Broughton, M. Basner, A. Kearney, L. Ikuma and M. Morris, "Minimum Acceptable Net," NASA, 2015.
- [24] Mars Architecture Steering Group, "Human Exploration of Mars Design Reference Architecture 5.0," NASA, 2009.
- [25] Science and Technology Policy Institute, "Evaluation of a Human Mission to Mars by 2033," Institute for Defense Analysis, Washington, DC, 2019.
- [26] F. E. Garrett-Bakelman, M. Darshi, S. J. Green, R. C. Gur, L. Lin and B. R. Macias, "The NASA Twins Study: A multidimensional analysis of a year-long human spaceflight," *Science*, vol. 364, no. 6436, 2019.

- [27] J. B. Charles and R. A. Pietrzyk, "A year on the International Space Station: implementing a long-duration biomedical research mission," *Aerospace Medicine and Human Performance*, vol. 90, pp. 4-11, 2019.
- [28] Human Research Program, "Standard Measures Cross-Cutting Project (SMCCP) Requirements Document, Baseline, November 28, 2018," NASA Johnson Space Center, Houston, 2018.
- [29] G. E. Clément, "Spaceflight Standard Measures," in prep..
- [30] M. L. Reagan, B. A. Janoiko, M. L. Parker, J. E. Johnson, S. P. Chappell and A. F. Abercromby, "NASA's Analog Missions: Driving Exploration Through Innovative Testing, AIAA 2012-5238," in *AIAA SPACE 2012 Conference & Exposition, 11 - 13 September 2012, Pasadena, California*, 2012.
- [31] J. D. Frank, K. McGuire, H. R. Moses and J. Stephenson, "Developing Decision Aids to Enable Human Spaceflight Autonomy," *AI Magazine*, vol. 37, no. 4, pp. 46-54, 2017.
- [32] J. J. Marquez, S. Hillenius, M. Healy and J. Silva-Martinez, "Lessons Learned from International Space Station Crew Autonomous Scheduling Test," *11th International Workshop on Planning and Scheduling for Space (IWPSS 2019); July 08, 2019 - July 10, 2019; Berkley, CA; United States*, p. 10pp, 2019.
- [33] M. Reschke, I. B. Kozlovskaya, I. S. Kofman, E. S. Tomilovskaya, J. M. Cerisano, J. J. Bloomberg, M. M. Stenger, S. M. C. Lee, S. S. Laurie and I. V. Rukavishnikov, "Sensorimotor Results from the Joint NASA and Russian Pilot Field Test," *2016 NASA Human Research Program Investigators' Workshop (HRP IWS 2016); February 08, 2016 - February 11, 2016; Galveston, TX; United States*, 2016.
- [34] M. F. Reschke, I. B. Kozlovskaya, I. S. Kofman, E. S. Tomilovskaya, J. M. Cerisano and M. S. Rosenberg, "Field Test: Results from the One-Year Mission," *2017 Human Research Program Investigators' Workshop*, 2017.
- [35] M. A. Rucker, S. Jefferies, A. S. Howe, R. Howard, N. Mary, J. Watson and R. Lewis, "Mars Surface Tunnel Element Concept," *IEEE Aerospace Conference, March 5-12, 2016, Big Sky, MT*, 2016.
- [36] Science and Technology Policy Institute, "Market Analysis of a Privately Owned and Operated Space Station," Institute for Defense Analysis, Washington, DC, 2019.
- [37] NASA, "NASA Plan for Commercial LEO Development," NASA, Washington, DC, June 7, 2019.
- [38] J. Crusan, R. M. Smith, D. Craig, J. M. Caram, J. Guidi, M. Gates, J. M. Krezel and N. B. Hermann, "Deep space gateway concept: Extending human presence into cislunar space," *2018 IEEE Aerospace Conference*, 2018.